Teaching Sustainability Analysis in Electrical Engineering Lab Courses

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***Abstract*—Laboratory courses represent an incompletely tapped opportunity to teach sustainability concepts. This work introduces and evaluates a simple strategy used to teach sustainability concepts in electrical engineering laboratory courses. The technique would readily adapt to other disciplines. The paper presents assessment data and a wiki containing student sustainability analyses.**

***Index Terms*—Electrical engineering education, integrated circuits, sustainability, systems engineering, technology social factors.**

I. Introduction

THE NEED TO educate students "to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability" has gained sufficient value and prominence to deserve its own ABET Program Outcome, Criterion 3(c) [1]. This work presents a strategy to introduce students to the relevant issues in earlier coursework and to provide practice enabling them skillfully to achieve such a program outcome in senior-level design coursework. After reviewing sustainability definitions, this paper describes a strategy whereby students take a systems approach to analyze sustainability issues and presents assessment data suggesting students were able to improve their sustainability analysis skills. The simple strategy has students write about sustainability issues associated with their weekly engineering laboratory experiments. As difficult as it may seem to incorporate sustainability into integrated circuit labs or other engineering labs, it may prove as easy as asking students to consider how their experiments relate to sustainability.

II. Sustainability Definitions

While numerous sustainability definitions exist, several nicely convey how sustainability depends on multidisciplinary and systems thinking. A definition from Euston and Gibson describes sustainability as "a condition in which natural systems and social systems survive and thrive together indefinitely" [2]. This approach naturally evokes the Venn diagram of Fig. 1 showing that sustainability can exist where *Environmental*, *Energy*, *Economic*, and social and political *Equity* considerations overlap. A lengthier list of "E" constraints could include *Ecology, Education*, and *Ethics*. A sustainable society allows each human being the opportunity to develop in freedom, within a well-balanced society and in harmony with its surroundings [3]. Fig. 2, found in an environmental engineering textbook [4], presents such a multifaceted view of sustainability. As described by McDonough, "the goal is a delightfully diverse, safe, healthy, and just world, with clean air, soil, water, and power, economically, equitably, ecologically, and elegantly enjoyed" [5]. To achieve sustainability, McDonough works to "design systems that love all the children of all species for all time" [5]. Such a multidisciplinary backdrop creates a more nuanced view of the original Brundtland Commission definition of sustainable development, which seeks a way to meet the needs of the present without compromising the ability of future generations to meet their own needs [6].

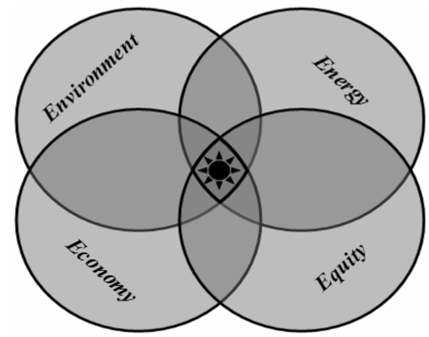

Fig. 1. Euston and Gibson definition of sustainability. Satisfying multidisciplinary constraints can create sustainability defined as ". . . a condition in which natural systems and social systems survive and thrive together indefinitely" [2], [7].

Sustainability is:

Safe
Universally accepted
Stable
Technology that benefits all
Antipollution
Improvement in quality of life
Nontoxic
Awareness
Beautiful
Indigenous knowledge
Least-cost production
Income
Total quality
Youth

Fig. 2. A multifaceted view of sustainability [4] (used with permission).

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III. Weekly Assignments

A. Learning Outcomes

The context for this work is the laboratory course EE 347, associated with a course titled *Digital Electronics and Integrated Circuits*, EE 307, given at California Polytechnic State University (Cal Poly). The courses form the second quarter of a three-quarter sequence of electronics courses during the junior year, following a year of introductory circuit analysis courses. EE 307 and EE 347 are required courses for Electrical Engineering and Computer Engineering majors. The general course learning objectives are the abilities to analyze, interface, simulate, implement, build, test, layout, and design integrated circuits for use in digital applications. More specific outcomes include the abilities to list, explain, distinguish, analyze, simulate, interface, and compare the voltage transfer characteristics, logic levels, transient characteristics, power dissipation, and fan-out of the major logic families. A complete list of learning outcomes appears online [8]. Compared to topics and outcomes described by the Computer Engineering 2004 Joint Task Force on Computer Engineering Curricula, Cal Poly course coverage corresponds approximately to Electronics areas CE-ELE3 through CE-ELE8, as well as a few topics in the VLSI areas [9]. The course also seeks to prepare students for a technical elective course in VLSI design and subsequent required courses in analog electronics, mixed-signal electronics, and digital design and embedded systems.

More generally, the course assists students to achieve ABET outcomes 3a, 3b, 3c, 3e, 3g, and 3k, and clearly emphasizes an ambitious list of technical topics rather than sustainability. Recognizing the situational factors acting to constrain course boundaries and student time, this attempt to teach sustainability learning outcomes in a laboratory course distilled two outcomes from the longer list of sustainability learning outcomes listed in Appendix I:

1) Articulate one or more definitions of sustainability.
2) Explain how EE 347 experiments relate to sustainability issues.

These two outcomes connect a modest subset (1, 4, 21, and 22) of those found in Appendix I.

B. Assignment Mechanics

The most recent course syllabus details course mechanics and the course schedules for reading, homework, laboratory experiments, lab reports, quizzes, and the final exam [10]. Primarily, the laboratory consists of weekly experiments [11], which the students document in weekly lab reports. Students receive detailed instructions on how to document their experimental work, analysis, and learning to the quality required by the IEEE in its professional journals and transactions [12].

The idea is to have students analyze sustainability issues associated with each experiment they perform in a new required section of their weekly lab reports. Specifically, each lab report must contain a required "Section II" explaining **how experiment topics, or applications related to the experiment, foster or prevent sustainability** [12]. The instructions for preparing lab reports include a two-paragraph set of instructions including a concise introduction to sustainability concepts along with a list of suggested references to consult [5], [13]–[15]. The instructions appear in Appendix II.

Because the course devotes most available class time to meeting its nonsustainability learning outcomes, the sustainability analysis teaching strategy has to consume minimal class time. As implemented, the instructor spends less than 10 min total discussing the sustainability analysis assignments with the whole class during the first two class meetings. Subsequently, students receive written feedback on their lab reports, including written feedback on the sustainability Section II. Some students also discuss the sustainability analyses with the instructor during lab sessions or office hours, just as some students discuss technical issues and technical applications of the weekly experiments.

Exposing students to several sustainability definitions can ease the resistance some feel when asked to connect technical engineering concepts to seemingly unrelated topics. Some students feel a similar resistance when expected to practice high-quality technical communication and critical thinking skills along with more technical problem-solving. Using the synergies between technical communication, critical thinking, sustainability analysis, and systems thinking can help students solve technical problems. Perhaps, teaching students to dispel the imagined barrier between engineering and sustainability can similarly improve their problem-solving skills. A desire to make multidisciplinary connections naturally segues into discussing Commoner's laws of ecology [16].

By writing sustainability analyses, students learn to explain how experiment topics and applications related to the experiments foster or prevent sustainability. Their analyses relate energy and resource consumption issues relevant to their technical coursework to sustainability issues involving environmental, social, political, and economic aspects. During the last few weeks of the course, students use a wiki to collaborate on their analyses. See http://sustainability-and-ICs.pbwiki.com/[17]. The wiki contains examples of sustainability analyses written by the students as part of their weekly lab reports. Ideas students publish via the wiki demonstrate their ability to expand the learning they typically achieve in such technical courses to systems thinking, connecting multiple interrelated nontechnical perspectives. The wiki enables students to read work from their colleagues and provide comments as feedback. Wiki submissions for Winter 2008 and Fall 2008 contain such student comments. The next section discusses results from assessments used to measure sustainability analysis skills.

IV. Assessment Results

The assessment uses two questions to measure if students can define sustainability and analyze sustainability issues associated with one lab experiment. The assessment also measures if exposure to the proposed sustainability teaching strategy makes any difference in students' performance on the assessment. Fig. 3 contains the sustainability assessment questions and the rubric designed to score student responses.

Course scheduling conveniently sets up experimental and control cohorts. Course offerings consist of multiple lecture sections containing 20–40 students and lab sections containing 16–24 students. Students completed the assessment in their lecture sections at the end of Winter and Spring quarters in

1. Write one or two definitions of sustainability.

a. 0 points if misses sustainability all together
b. 1 point for a vague definition related to sustainability
c. 2 points for a clear definition close to either the Brundtland definition, Euston and Gibson definition, McDonough & Braungart definition, or another accepted definition

Brundtland	Sustainability allows people to meet the needs of the present generation without compromising the ability of future generations to meet their own needs.
Euston & Gibson	Sustainability describes a condition in which natural systems and social systems survive and thrive together indefinitely
McDonough & Braungart	"Design systems that love all the children of all species for all time" or "The goal is a delightfully diverse, safe, healthy, and just world, with clean air, soil, water, and power, economically, equitably, ecologically, and elegantly enjoyed."

d. 3 points for a clear definition incorporating more than one accepted definition

2. Select one EE 347 experiment and explain how it relates to sustainability issues.

a. 1 point for each connection to energy, economic, environmental, social and political equity, and ethics
b. 1 point for each connection to a law of ecology

- Everything connects to everything else
- Everything must go somewhere
- Nature knows best and bats last
- There is no such thing as a free lunch

c. 1 point for weaving in more than one EE 347 experiment

Fig. 3. Sustainability assessment and scoring rubric [2], [5], [6], [16]. Questions appear in bold type, and the rubric follows each question.

2008 as "pop" quizzes. A score depending on effort contributed modestly to the course grade (1%), but the description below only reports the score obtained using the rubric of Fig. 3. During both quarters, the author taught all lecture sections and three lab sections. The author required students to complete the required sustainability analyses in their lab reports, with the analyses counting for up to 10% of a weekly lab report score. Other instructors taught the remaining lab sections and did not require students to complete the sustainability analyses. "Experimental" cohorts contain students who performed the sustainability analyses in their lab sections. "Control" cohorts contain students whose lab sections did not include the sustainability analyses.

Fig. 4 presents the assessment results as a box plot. The boxes compare student sustainability assessment scores for the "Experimental" and "Control" groups from two quarters. The average scores for the "Experimental" groups (4.34 and 4.04) exceed the average scores for the "Control" groups (2.31 and 2.86). Differences in average scores are statistically significant ($P = 0.000$ in Spring quarter and $P = 0.011$ in Winter quarter). Large effect sizes result (1.2 and 0.72) even though each quarter's data have large standard deviations (>1.6). On average, students completing the sustainability analyses in their lab reports score higher on the sustainability assessment, indicating more advanced conceptual development [18].

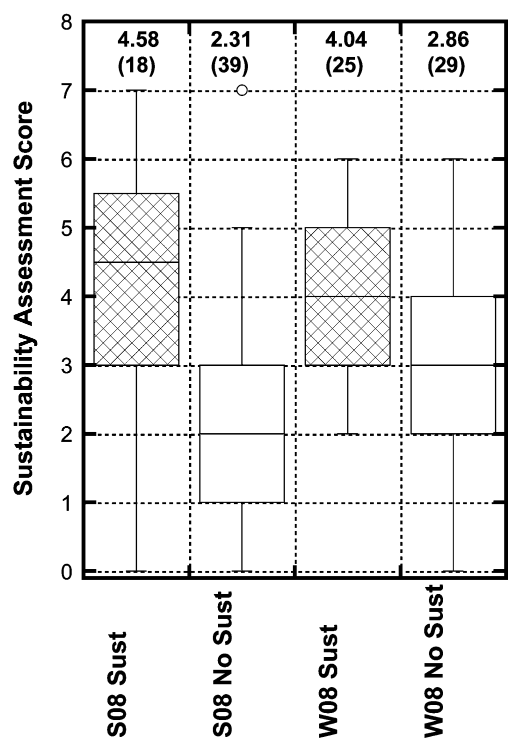

Fig. 4. Sustainability analysis assessment results. The box plots compare experimental cohorts (hatched) with control cohorts for the assessment administered during two quarters, Spring 2008 (S08) and Winter 2008 (W08). Each experimental cohort contains students whose lab sections did the sustainability analysis. Each control cohort contains students whose lab sections did the same experiments but not the sustainability analysis. Numerical values indicate average scores for each cohort with sample size in parentheses.

V. Conclusion

This work has proposed, implemented, and assessed a technique to teach sustainability concepts within engineering laboratory courses. The technique asks students to analyze and write about sustainability impacts of experiments performed and applications of those experiments. Students share best practices and learn from each other via a wiki established for this purpose [17]. Assessment data support a conclusion that the proposed teaching technique advances students' abilities to define sustainability and analyze sustainability issues. The technique is sufficiently general as to allow its use in disciplines other than electrical engineering. The technique lays a foundation for engineering students to learn and apply more general systems engineering and sustainability skills such as those outlined in Appendix I.

To place this work in context, the literature suggests teaching sustainability via dedicated lectures, case studies, projects, and integration into the overall curriculum [19]–[21]. The Association for the Advancement of Sustainability in Higher Education lists curriculum resources on its Web site, which include sustainability degree programs and specific courses with discipline-specific listings for engineering [22]. This work addresses the lack of resources available to instructors who wish to teach sustainability concepts within technically intensive engineering courses, particularly in programs that cannot add more courses. The assessment data in Section IV measure cognitive achievements, but further work would be required to blend psychomotor and effective learning outcomes also suggested as useful for sustainability instruction [23], [24].

Should any instructors from other institutions and disciplines eventually use and assess this or related techniques in their courses, the author would greatly appreciate learning about their results.

Appendix I
Sustainability Learning Outcomes

The following list of sustainability learning outcomes derives from [25] as engineering-specific ways to teach more general sustainability learning outcomes [18], [26], [27].

1) Define the concept of sustainability.
   - a condition in which natural systems and social systems survive and thrive together indefinitely [2].
   - meeting the needs of the present without compromising the ability of future generations to meet their own needs [6].
   - allows each human being the opportunity to develop in freedom, within a well-balanced society and in harmony with its surroundings [3].
2) Perform life cycle analysis and design.
3) Perform design for reuse.
4) Identify and quantify the impacts of energy and natural resource consumption during a product lifecycle.
5) Identify and quantify the impacts of energy and natural resource consumption during a graduate's life.
6) Calculate the environmental footprint of a project over its lifecycle.
7) Explain the impacts of engineering projects in a societal context, including but not limited to the context of general education courses.
8) Apply systems thinking to engineering problems and projects [28].
9) Use international environmental management standards (ISO 14000, EMAS, etc.).
10) Define multidisciplinary teams as groups of individuals each working separately on his or her "piece" of an overall problem [29].
11) Perform successfully as a member of a multidisciplinary team.
12) Define interdisciplinary teams as groups of people who focus not on "their" component of a problem, but collaboratively on the entire problem through the lens of their particular expertise [29].
13) Perform successfully as a member of an interdisciplinary team.
14) List the 10 points in the Talloires declaration [30].
15) Apply the goals of the Talloires declaration to engineering studies and careers.
16) Predict the long-term contributions of an engineering graduate throughout their career to the state of the planet's resources.
17) Predict the career impacts of resource consumption by an engineering graduate.
18) Consider the probability of unanticipated consequences of technical policies and strategies.
19) Articulate the concept of the Tragedy of the Commons [31].
20) Apply the concept of the Tragedy of the Commons to current commons in engineering, including but not limited to the electric grid, the internet, bandwidth, computing power, other technical resources, and natural resources.
21) Articulate Commoner's laws of ecology [16]:
    "Everything is connected to everything else."
    "Everything must go somewhere." (waste equals food)
    "Nature know best."
    "There is no such thing as a free lunch."
22) List some "E"s of sustainability: Ecology, Economy, Education, Energy, Environment, Equity, and Ethics.
23) Define ecosystem services as the benefits people obtain from ecosystems [32], [33].
24) Identify and measure the impacts of a project on ecosystem services.
25) Identify the internal and external stakeholders of a project.
26) Measure the impacts (costs and benefits) of a project on all present and future stakeholders.
27) Measure the economic impacts (costs and benefits) of a project on all present and future stakeholders.
28) Articulate the ethical, social, and political impacts of a project on all present and future stakeholders.
29) Develop and pursue a political strategy to implement a project.

Appendix II
Sustainability Issues Instructions

Instructions for required Section II of lab reports [12]:

Use this section to analyze sustainability issues associated directly or indirectly with your experiment. Sustainability describes a condition in which natural systems and social systems survive and thrive together indefinitely [2]. A sustainable condition allows people to meet the needs of the present without compromising the ability of future generations to meet their own needs [6]. Because humanity now consumes and pollutes the Earth's resources faster than natural and human systems can replenish and clean them, we do not currently live in a sustainable manner [32], [33]. It might prove helpful to consider Commoner's laws of ecology, which sound unsurprisingly similar to laws of physics:

- *Everything connects to everything else*

- *Everything must go somewhere*
- *Nature knows best and bats last*
- *There is no such thing as a free lunch* [16].

Explain how experiment topics or applications related to the experiment foster or prevent sustainability [12]. Reference [13] and others on Blackboard™ provide helpful information. Consider issues related to *Energy*, *Environment*, *Economics*, and social or political *Equity*, four "E"s of sustainability.

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